Enhanced Wireless Multiple-Access and Scheduling Techniques Using Positional and Environmental Information

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***Abstract*—This paper proposes a number of novel uses for 3D location and environmental geometry information to enhance the performance of the wireless physical layer. In the context of this paper, such information is obtained in real-time from a mobile operative carrying the ViewNet system. A location-based multi-user scheduler is proposed to exploit multi-user diversity by choosing users with wide angular separation. If SINR feedback is also available, an SINR-based scheduler with location-assistance is developed to further enhance the system performance. These schedulers are then combined with a modified proportional fair scheduler based only on location information, which does not incur data-rate feedback requirements. Finally, the ability to associate rate and other parameters to location allows the prediction of future rate values and a family of novel scheduling methodologies are proposed to take advantage of this.**

***Index Terms*—ViewNet, location information, scheduling.**

I. INTRODUCTION

The exploitation of location information is increasingly relevant to wireless systems as it becomes more readily available. Improved resource allocation and communication system performance can be achieved [1] by leveraging up-to-date location information from emerging augmented reality applications, such as the ViewNet project [2]. The ViewNet system is able to capture, in real-time, accurate 3D information about the physical shape of the environment and the locations of wireless terminals within it. The core of the system is a visual simultaneous localization and mapping (VSLAM) application which provides the 3D local coordinates of a moving camera while at the same time mapping the surrounding environment based on observations within the video stream [3]. The absolute location of the camera is obtained by an ultra-wideband (UWB) positioning system if indoors or GPS if outdoors.

Beamforming (BF) is a well established method to grant access to specific terminals based on decisions as to which of them should have possibly concurrent access to the wireless resources. This requires the use of additional bandwidth and data exchange due to the feedback load this imposes, as well as processing delay to obtain the relative positions of users via potentially sophisticated angle-of-departure methods [4]. In ViewNet, on the other hand, the coordinates of all terminals are available directly from the application without additional processing or bandwidth.

Additionally, ViewNet's 3D environmental mapping capability allows low-resolution ray-tracing to predict the data rates in the vicinity of the users in a system. Coupled with extrapolation of their recent route along e.g. a straight line, predictions of future data rates can be made. Alternatively, a 'fingerprint' map of the area can be constructed which gives the rate achieved by earlier visitors to a given coordinate.

TABLE I
OFDM DOWNLINK SIMULATION PARAMETERS

Transmission Bandwidth	100 MHz
Operating Frequency	5 GHz
FFT Size	1024
Useful Sub-carriers	768
Guard Interval Length	176
Sub-carrier Spacing	97.656 kHz
Users	10 or 25
Tx Power Level	17 dBm
Noise figure	-94 dBm

In this paper, a set of low-complexity and low-feedback scheduling strategies are developed which use location information from sources such as ViewNet to improve the performance of beamforming systems. These are investigated for certain key propagation and modeling scenarios and varying numbers of users. In addition to reducing the feedback and computation requirements of beamforming, the location information is used to propose a proportional fair scheduler (PFS) based only on location information which is combined with beamforming and achieves good fairness without requiring data-rate feedback.

Finally, using the information about future data rates available from such systems leads to a new wireless scheduling methodology utilizing both the past information common to existing schedulers and also the future information available from augmented reality systems like ViewNet. Such a scheduler utilizes a class of information that is never normally available, so opening up new possibilities in scheduler design.

II. SYSTEM AND CHANNEL MODELLING DESCRIPTION

OFDMA is one of the most promising PHY and multiple access candidates for future communication systems. The WiMAX standard (IEEE 802.16) uses OFDMA as the air interface and the 3GPP LTE adopts OFDMA in the downlink.

Considering a multi-user scenario, the total system bandwidth is divided into sub-channels, termed as physical resource blocks (PRBs), which can then be allocated to different terminals for multiple access purposes. The key parameters

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of the OFDMA downlink system considered here are given in Table I. There are 48 PRBs in the 100 MHz system, each consisting of 16 adjacent sub-carriers.

A. Beamforming

Assume that the basestation (BS) is equipped with a uniform linear array (ULA) consisting of N_T antenna elements with spacing Δ of half a wavelength λ, and there are K wireless terminals $1, 2, \ldots, K$ each with a single receive antenna. Consider that a user of interest, k, is in the azimuthal direction θ_k from the axis of this antenna. In ViewNet, θ_k can be obtained from the location information of the wireless terminals which are known at the base station. In the frequency domain, let $\alpha_{k,s}$ be the complex amplitude of the channel from the BS to user k on OFDMA subcarrier s and $X_{k,s}$ its matching unit-power data symbol. Define its beamforming weight vector to be $\mathbf{W}_{k,s} = \left[1, e^{j2\pi\Delta\cos\theta_k}, \ldots, e^{j2\pi(N_T-1)\Delta\cos\theta_k}\right]/N_T$. Then user k's received vector signal is [5]:

$$\mathbf{r}_{k,s} = \alpha_{k,s}\mathbf{W}_{k,s}X_{k,s}, \tag{1}$$

which is summed over space at the single receive antenna into $Z_{k,s} = \sum_{i=1}^{N_T} \mathbf{r}_{k,s}(i)$. The capacity of a single user beamforming scheme without inter-user interference is:

$$C_{k,s} = \log_2\left(1 + \mathrm{SNR}\left|\alpha_{k,s}\mathbf{W}_{k,s}\right|^2\right) \ \text{bps/Hz}, \tag{2}$$

where $|\cdot|$ denotes the relevant norm, and user k's SINR is [5]:

$$\frac{P_k\left|\alpha_{k,s}\mathbf{W}_{k,s}\right|^2}{\sum_{j\neq k} P_j\left|\alpha_{k,s}\mathbf{W}_{j,s}\right|^2 + \sigma_{k,s}^2}, \tag{3}$$

with P_k and $\sigma_{k,s}^2$ the user's signal and noise powers.

B. Channel Model Parameters

The simulations that follow use the statistical ETSI BRAN channel model 'C' [6], which represents a typical large open space (indoor or outdoor) in non-line-of-sight (NLOS) conditions. It has a sampling period of 10 ns and an RMS delay spread of 150 ns.

1) Scenario 1: Wireless terminals are placed at equal distances from the base station. They are randomly distributed within a sector of 120° and experience the same SNR at 0 dB.

2) Scenario 2: Wireless terminals experience different received SNRs, based on their distance d_k from the serving BS in a range of 100m in radius. Path loss is modelled based on the specifications in 802.11n [7]. This model consists of free space path-loss (index of 2) up to a breakpoint distance $d_{\mathrm{bk}} = 30$m and an index of 3.5 after this.

III. Location Based Multiuser Schedulers

A. Location-Based Scheduler for Multi-user Beamforming (LBS)

Multiple beams can be formed and separated in different beamforming directions if location information of different wireless terminals is known. Instead of searching through all possible sub-sets of terminals, a low-complexity location-based multi-user beamforming (MU-BF) scheduler is proposed here which aims to select a sub-set of wireless terminals that have a large inter-terminal angular separation in azimuth. The scheduler initially selects a targeted wireless terminal in a round-robin fashion, and then selects up to $N_T - 1$ terminals which are angularly far away from each other for transmission. Define the set of all terminals $\kappa = \{1, 2, \ldots, K\}$.

1) Initialization:

- *Evenly divide the considered angular range Φ into N_T sub-sectors, each sub-sector covering an angular range of $[(i-1)\Phi/N_T, i\Phi/N_T]$.*
- *Select a wireless terminal a_1 in a round-robin fashion and set $A_c(1) = \{a_1\}$.*
- *Identify the sub-sector S_1 that a_1 is located in, and rank the other sub-sectors based on their angular separation to sub-sector S_1 in descending order.*

2) For $i = 2$ to N_T (start from the sub-sector furthest away from a_1):

- *Find the group of wireless terminals $B_c(i) \in \kappa$ within sub-sector S_i.*
  If $B_c(i) \neq \emptyset$:
  Find $a_i = \arg\max_{k\in B_c(i)}\left(\min_{j\in A_c(i-1)}|\theta_k - \theta_j|\right)$.
  Set $A_c(i) = A_c(i-1) \cup \{a_i\}$.
  Else if $B_c(i) = \emptyset$:
  $A_c(i) = A_c(i-1)$, scheduling fewer than N_T users.

The performance of this algorithm depends on the exploitation of multi-user diversity and therefore it requires a sufficient number of terminals to be available in the environment if a large number of terminals are to be supported simultaneously.

B. SINR-based Scheduler for Multi-user Beamforming with Location Information (SBS)

In addition to location information, if channel information (SINR) is also available at the BS, a performance improvement can be achieved over the location-only based BF. Let A_c denote an arbitrary sub-set of κ. For PRB c, if the index of the starting sub-carrier is m and finishing sub-carrier is n, according to the rate-optimal greedy algorithm, the sub-set A_c^* achieving the highest overall rate is scheduled:

$$A_c^* = \arg\max_{A_c\in\kappa} \sum_{i\in A_c}\sum_{s=m}^{n} \log_2\left(1 + \mathrm{SINR}_{i,s}\right). \tag{4}$$

This rate greedy scheduler has to search all possible sub-sets of terminals and find the one achieving the highest possible overall rate. Therefore, the computation complexity is high, especially when the number of wireless terminals is large. An alternative reduced-complexity and sub-optimal rate greedy scheduling approach for beamforming is suggested here. The targeted terminal is initially chosen in a round-robin fashion. Then at each step, a terminal that maximizes the overall rate R_{BF}^c is added to the chosen terminal subset. The process terminates if none of the remaining terminals can further increase the overall rate, i.e. the multi-user interference caused by adding a further terminal negatively affects the overall rate performance. Note $\cdot \setminus \cdot$ denotes set subtraction.

1) Initialization:

- *Set $i = 1$.*
- *Select a terminal a_1 in a round-robin fashion.*
- *Set $A_c(1) = \{a_1\}$ and denote the achieved rate $R^c_{BF} = R_c(A_c(1))$.*

2) For $i = 2$ to N_T:

- *Find a terminal:*
  $a_i = \arg\max_{k\in\kappa\setminus A_c(i-1)} R_c(A_c(i-1) \cup \{k\})$.
  If $R_c(A_c(i-1) \cup \{a_i\}) > R^c_{BF}$:
    Set $A_c(i) = A_c(i-1) \cup \{a_i\}$.
    Set $R^c_{BF} = R_c(A_c(i-1) \cup \{a_i\})$.
  Else:
    No increase in rate is achieved and exit the loop.

IV. Location-Based Proportional Fair Scheduler

For the initial selection of the targeted terminal for the schedulers in Section III, if a greedy approach is adopted, the majority of the resources are unfairly allocated to the terminals which are closer to the transmitter and thus tend to have higher SINR. A simple solution to improve fairness is to select the targeted terminal in a round-robin fashion as suggested in Section III, which may degrade the overall rate performance due to inefficient exploitation of multi-user diversity. In addition, the multi-user schedulers in Section III can only be applied to an OFDMA system on a per-PRB basis, and therefore the scheduling decisions on all PRBs are independent. Throughput fairness among users with non-identical channel quality statistics can be improved by the PFS [8]. The PFS in [8] requires the feedback of effective signal-to-noise ratio (ESNR) from all terminals to compute the current rate required by the scheduling decision metric.

In this part, a PFS based on location information (LB-PFS) is proposed for a beamforming OFDMA system to improve the fairness performance of the location-based multi-user schedulers. A targeted wireless terminal is selected based on the decision of this location-based PFS. It works on the presumption that wireless terminals closer to the BS generally have higher received SNR resulting in better data rate. The scheduler computes the average distance $T_k(s)$ in a past window of length t_c and transmits to the terminal k^* with the lowest metric $m_k(t) = d_k(t)/T_k(s)$ at PRB c at time t. The average distance $T_k(s)$ is updated as follows:

$$T_k(t+1) = \begin{cases} (1-1/t_\mathrm{c})\,T_k(t) + (1/t_\mathrm{c})\,d_k(t), & k \neq k^* \\ (1-1/t_\mathrm{c})\,T_k(t), & k = k^*, \end{cases} \tag{5}$$

where $s = t \times C + c$, and C is the total number of PRBs per OFDM symbol. Due to the different distances from the BS, the wireless terminal closer to the BS is generally much stronger than the other wireless terminals on average, although channels fluctuate due to multipath fading. In the proposed PFS, wireless terminals do not compete for resources based on their absolute transmitter-receiver (Tx-Rx) distances $d_k(t)$ but after normalization by their respective average Tx-Rx distances $T_k(s)$. The wireless terminal with a shorter Tx-Rx distance will be initially scheduled to transmit but having a decreasing average distance. In contrast, the wireless terminals far away from the transmitter will gradually have a higher average Tx-Rx distance and therefore a reduced $d_k(t)/T_k(s)$ value. Thus, the algorithm schedules a wireless terminal when its Tx-Rx distance is low relative to its own average Tx-Rx distance over the window of length t_c. As the scheduling window length increases, the change in average distance $T_k(s)$ of each wireless terminal becomes less significant and the scheduling algorithm then gradually reduces to always picking the wireless terminal which is closest to the transmitter.

V. Future-based Scheduling

The proposal here is to augment the scheduling metric in order to include some form of information about the future values of rate $R_k(t)$ that the users will experience. This is done by adding to the numerator and/or denominator of the PFS's $m_k(t)$, a weighted average of the future throughputs:

$$m^F_k(t) = \frac{\alpha R_k(t) + \gamma F^\mathrm{N}_k(t)}{\beta T_k(t) + \delta F^\mathrm{D}_k(t)}, \tag{6}$$

where α, β, γ, δ can be any scalars and the two future-based functions $F^\mathrm{N}_k(t)$ and $F^\mathrm{D}_k(t)$ can be the same or different. The following possibilities are considered in this paper, where $F_k(t)$ is shorthand for either of $F^\mathrm{N}_k(t)$ and $F^\mathrm{D}_k(t)$. The future track of $R_k(t)$ is considered over N future scheduling points.

A. Future weighting

$F_k(t)$ is an exponentially-decaying weighted average forwards from t_0, as $T_k(t)$ is backwards:

$$F^1_k(t) = (1/N)\sum_{n=1}^{N}(1-1/t_\mathrm{f})^n\,R_k(t+n). \tag{7}$$

This assigns most weight to throughputs that are in the near future and exponentially less to those further away. If $F^\mathrm{N}_k(t) = F^1_k(t), F^\mathrm{D}_k(t) = 0$ (denoted FWN), this function will reward high throughputs in the near term over those far away, whereas if $F^\mathrm{D}_k(t) = F^1_k(t), F^\mathrm{N}_k(t) = 0$ (denoted FWD), it will penalize them. N controls how far into the future the scheduler assigns any weight at all to R_k, and t_f is to the future what t_c is to the past. Such a formulation fits the ViewNet scenario where it may be possible to predict a user's track in the near future e.g. by extrapolating along a straight line from their recent track, but with less certainty at greater time lags.

B. Future sliding window

The second proposal is to actually compute $T_k(t)$ over both the past and future windows, again with the over-optimistic assumption that user k transmits at all the N future time-slots (denoted TXA). By repeated application of the $k = k^*$ portion of (5), the result is:

$$\begin{aligned} T_k(t+N) = {} & (1-1/t_\mathrm{c})^N\,T_k(t) + \\ & (1/t_\mathrm{c})\sum_{n=1}^{N}(1-1/t_\mathrm{c})^{n-1}\,R_k(t+N-n). \end{aligned} \tag{8}$$

TABLE II
AVERAGE JFI VALUES OF MU-BF WITH SCHEDULING ALGORITHMS

	10 users			25 users		
TX antennas	4	6	8	4	6	8
LBS	0.55	0.63	0.72	0.32	0.39	0.44
SBS	0.76	0.77	0.78	0.65	0.66	0.67

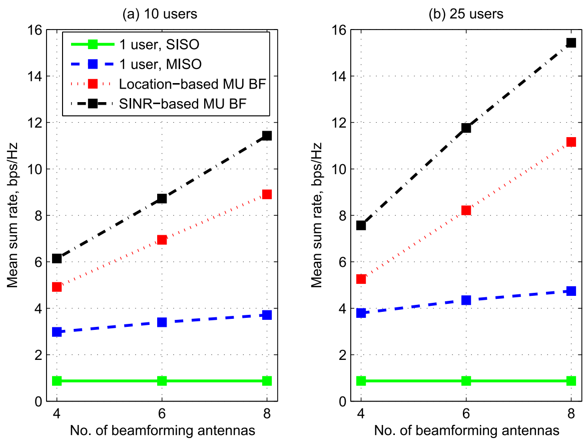

Fig. 1. Sum rate of LBS and SBS with round-robin initialization and (a) 10; or (b) 25 users. SNR = 0 dB.

This effectively has the reverse scheduling characteristics to the option discussed above, since $(1 - 1/t_c) < 1$. The expression in (8) can be viewed in the form of (6) with β the coefficient of $T_k(t)$ and $F_k^{\mathrm{D}}(t)$ the second line in (8).

C. Full Rescheduling over Future Window

The final proposal is a full re-scheduling at each of the N future scheduling instants. That is, to slide the scheduler forwards, re-compute the scheduling at each slot and use this to produce, at the N^{th} scheduling slot, a new estimate for T_k which is then used directly in calculating $m_k(t)$. This requires no explicit future rate measure, so effectively $\gamma = \delta = 0$. Of course, the two proposals above could be incorporated into the scheduling in this proposal also. 'Full future' scheduling is denoted 'FFS'.

VI. PERFORMANCE EVALUATION

The fairness performances of different schemes are evaluated using Jain's fairness index (JFI) [9]. The JFI varies between 0 and 1 and a larger JFI value indicates better fairness.

A. Performance of LBS and SBS in Scenario 1

The MU scheduling algorithms proposed in Section III are initially examined in Scenario 1. Employing multiple antenna elements in the array allows the formation of physically separated multiple beams to support MU transmission and achieve better overall rate compared to single-user beamforming as shown in Fig. 1. The number of elements in the array indicates the maximum number of users that can be supported simultaneously. A single-user single-antenna system is also plotted as a reference. Adopting the LBS with the initial user chosen

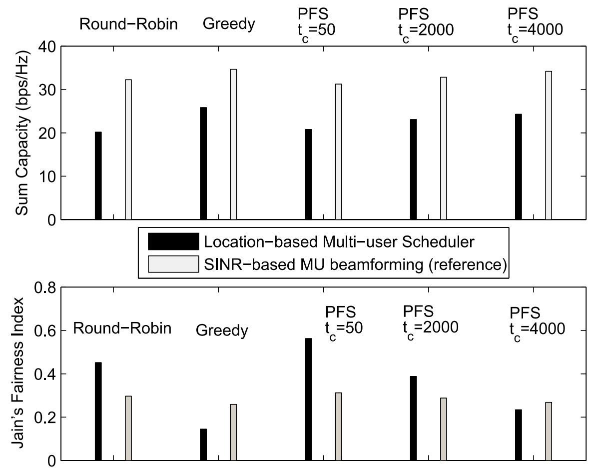

Fig. 2. Sum-rate and JFI for LBS and SBS with LB-PFS initialization. $N_T = 4$.

round-robin, as the number of supported wireless terminals increases, the data rate improvement due to antenna element gain and MU diversity gain becomes much more significant. The fairness performance also improves as more terminals are allowed for transmission simultaneously as shown in Table II. If SINR knowledge is available at the base station, then SBS (again with round-robin intialization) can exploit MU diversity more effectively for any array size to achieve an even better data rate as shown in Table II. With more users in the system, MU diversity allows selection of terminals with stronger channel conditions and less interference. As a result, although the same trend in rate and fairness improvement is observed as the number of antenna element increases, the overall rate achieved with 25 users is higher than with 10. The decrease in fairness is due to more competition for resources.

This achievable rate based on the SBS is considered as the reference rate in the paper. The results also show that the LBS is able to achieve a significant percentage of the reference rate (about 70% in Fig. 1(b)) and tends to perform better as the number of supported users increases with N_T.

B. Performance of LBS and SBS with LB-PFS initialization in Scenario 2

For wireless terminals experiencing independent channel conditions and received SNRs, fairness in resource allocation can be improved by applying the PFS as discussed in Section IV. An example of a 4-element BS is considered, which can support up to 4 simultaneous users. The performance of LBS and SBS with the initial user chosen using the LB-PFS is compared to the greedy and round-robin approaches in Fig. 2, for a 25-user system.

In the greedy approach, the targeted wireless terminal is always chosen to be the one closest to the transmitter resulting in the poorest fairness performance, though achieving the highest rate. The round-robin approach allows all the wireless terminals to have access to the resources, but the overall system rate is severely degraded. Compared to the greedy and

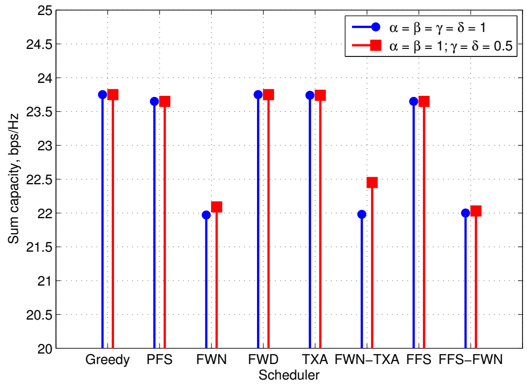

Fig. 3. Capacity for $\alpha = \beta = 1$ and $\gamma = \delta = \{1 \text{ or } 0.5\}$. $E_b/N_0 = 20$ dB.

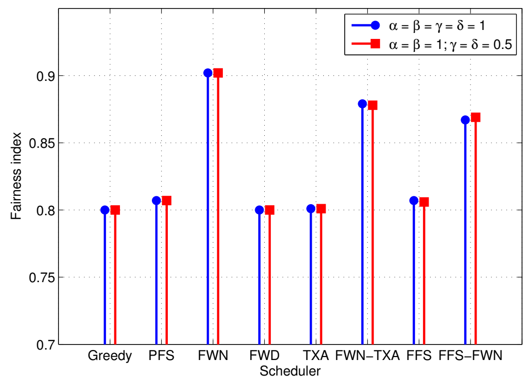

Fig. 4. Fairness index for $\alpha = \beta = 1$ and $\gamma = \delta = \{1 \text{ or } 0.5\}$.

round-robin approaches, the resource allocation of different PRBs in the LB-PFS is no longer independent as each PRB is assigned based on the scheduling history of previous PRBs. The LB-PFS allows the window length to be scaled to meet a specific fairness and rate performance. With increased window length, distance is averaged over a longer scale and the scheduler can afford to allocate resources to the wireless terminals that are closer to the transmitter and generally have better channel qualities. Thus, fairness performance degrades and rate approaches the greedy algorithm.

C. Future-based Scheduling

Results for the future-based scheduling proposals are shown with the same OFDMA system as in Table I. The wireless channels are 3000 realizations of the ETSI BRAN 'C' model [6], as in Scenario 1, but with fixed $E_b/N_0 = 20$ dB and $N = t_f = t_c = 300$. The total capacity available to each user k in a given PRB at time t is used as $R_k(t)$, with scheduling metrics for each user updated every step of t.

In Fig. 3, the effects on capacity of the various scheduling options are shown for an example set of values of the scalar parameters, with the corresponding JFIs in Fig. 4. The schedulers based on future information show a clear increase fairness, and some trade-off in terms of capacity. However, the capacity falls are small - about 1.5 bps/Hz on a value of 23 bps/Hz, while the improvements in fairness are up to 0.1 on an already-high index value of about 0.8. It is clear in Fig. 4 that a range of fairness-capacity trade-offs are available, but that the FWN+TXA combination performs most usefully, and prefers to have $\alpha = \beta = 1; \gamma = \delta = 0.5$. In this case, the capacity gap is smallest, but there is almost no change in fairness from having all scalars at unity. The fairness improvement using the future measure in the numerator arises since it acts to smooth out temporary dips in rate by compensating for them in the scheduling metric with near-term increases in rate. With $\gamma < \alpha$ or $\delta < \beta$, the future is weighted less than the present/past, and as γ and δ fall, the PFS is approached.

VII. Summary

The availability of up-to-date location and environmental geometry information to the wireless terminals in ViewNet provides an opportunity for the scheduler of the system to be enhanced in a number of novel ways. These methods are unique in that they rely on either very low feedback, thus freeing up forward bandwidth for application data, or on the ability to predict future data rate values of the users. A multi-user scheduling strategy chooses angularly separated users in order to select a set which experience reduced mutual interference. This provides a significant proportion of the reference scheme, a beamforming-based SINR selection scheme which exploits MU diversity effectively. A PFS which also takes advantage of location information is proposed to improve the system fairness in addition to the rate improvement achieved by the location-based schedulers. Finally, the ability to predict future data rates is incorporated into a new scheduling methodology which increases fairness compared to classical 'future-blind' schedulers in exchange for minimal rate loss.

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